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## **Linac H<sup>-</sup> Ion Source R&D Program**

### **Motivation:**

The Linac presently delivers a 400-MeV H<sup>-</sup> beam to the Booster with an intensity of 45-55 mA. The typical normalized emittance is ~7-8 ? mm mrad and the momentum spread is ~0.25% (both for 90% of the beam). It has been shown with protons that an intensity of ~80 mA can be transmitted through both the low- and high-energy linacs without significant changes in the RF systems and little increase in the losses. This is about the maximum for the Linac without major modifications in the RF systems or injection to the Linac. Obtaining 80 mA from the Linac requires 115+ mA from the ion source using the Cockcroft-Walton since only 70% of the continuous source beam can be effectively bunched and captured into linac buckets at injection. Except for the 30% loss at injection due to RF capture the other beam losses are only a few percent. At injection there is also a significant emittance growth in the beam due to errors in the earliest part of the Linac. Therefore, the motivation for ion source R&D is to increase the source intensity to increase the Linac output; while also increasing the source brightness (lower the beam emittance) to decrease the Linac losses and radiation levels as the intensity and repetition rates increase.

### **Program:**

An H<sup>-</sup> source R&D program is proposed below. This effort will involve: (1) work on improvements to the present magnetron source (planotron in Russian) to increase the H<sup>-</sup> beam intensity and brightness; and (2) work on a semi-planotron source (basically half of a magnetron), which could replace the magnetron source and produce a noiseless beam of 110+ mA with high brightness.

### **Improvement of the magnetron:**

The emittance (brightness) of the present magnetron may be improved by optimizing the discharge geometry, gas injection, extraction and plasma over-neutralization. The goal is to attain a reliable 85-100 mA of H<sup>-</sup> with an emittance of 0.5 ? mm-mrad (90%, normalized), which is a factor of two smaller than the present 750-keV beam emittance.

### **Development of a noiseless semi-planotron:**

Here, the goal is to obtain 110+ mA of  $H^-$  beam at 750 keV with an emittance of  $0.7 \text{ ? mm-mrad}$  (90%, normalized). This source is small so it could be adapted for installation in the Cockcroft-Walton as a replacement to the magnetron.

This program represents a first step for improving the Linac beam. It is a fairly short program (1-2 years) and requires moderate investment (a new hire plus \$60k M&S funds). If successful and the Booster responds favorably to the beam, this effort may have a small impact on the present Linac and Booster performance. This is because these new sources can be mounted on the Cockcroft-Walton and provide an  $H^-$  beam with higher intensity and better quality (*i.e.*, a brighter beam). Decreased beam size in the Linac should decrease the beam loss and radiation allowing higher intensity and repetition.

It is recognized that for a significant future improvement of the  $H^-$  beam quality for the existing Linac and future Proton Driver it would be necessary to develop an  $H^-$  source giving a very high brightness, such as a Penning geometry Surface-Plasma Source, known as a Dudnikov type  $H^-$  source, or other source that could be fitted to an RFQ accelerator, which would replace in some manner the first two MeV of Linac tank one.

Status:

Active work on the magnetron  $H^-$  source has not been done for sometime. Still the test bench and most of the parts and power supplies are in the ion source lab. Restarting this effort is not too difficult. An Associate Scientist has recently been hired into the Linac Group for this purpose. He is to begin July 1. It appears that some magnetron studies will be underway within a few months. In addition to this person, Vadim Dudnikov and Chuck Schmidt will give some assistance to this effort.

Some work on the semi-planotron has been done recently on the test stand to develop a low-intensity high-brightness DC beam for the electron cooling program. This would need considerably more work before it could replace the operating source.

Basic steps for beginning this program are:

1. Once a new group is formed, begin reestablishing the ion source test stand and begin operation of a standard Fermilab magnetron source.

2. Reinstallation of an emittance scanner, some beam diagnostics and computer acquisition system.
3. Begin studies on the source to understand present operation. An early goal is the characterization of an existing magnetron source beam: emittance scanning for optimal operation condition.
4. Consider source modifications and improvements.
5. An optimization of the discharge electrodes, gas pulsing system, and extraction system of the magnetron. An optimization of the space-charge neutralization with a plasma source. Test operation of the discharge electrodes, gas pulsing system, and extraction. Test long term operation.
6. Move on to the development of asemi-planatron surface plasma source.

## 3.1 Proton Source

### 3.1.1 Linac

Linac delivered H<sup>-</sup> beam with energy 400 MeV, intensity 47 mA. Acceleration of proton beam with intensity up to 80 mA was tested successfully. With production of H<sup>-</sup> beam of higher brightness from ion source it is possible to have a smaller beam size in linac, have higher intensity with a smaller beam loss and smaller radiation.

#### 3.1.1.1 Ion Source

Ion Source- is a source of life for all chain of Fermilab accelerators. Beam brightness could not be improved after extraction from the ion source. Improve beam brightness from the source is important for reducing an emittance growing in linac, for reducing a beam loss and radiation with a higher intensity and repetition.

### **Short R&D Program for Advanced H<sup>-</sup> Source Development and Adaptation**

A short (one year) H<sup>-</sup> source R&D program is proposed. The goal is to improve an H<sup>-</sup> beam quality- brightness by produce two new sources: (1) an improved magnetron, which would increase the H<sup>-</sup> beam brightness by a factor of two; and (2) a noiseless semi-planotron, which would increase the H<sup>-</sup> current to 110 mA with high brightness.

#### 1. Motivation:

At the recent proton driver review, the committee report recommended that the ion source “*should be an area of highest R&D priority*” for the ion source/linac part of the proton driver project. We fully concur with this recommendation. However, due to limited resources, we plan to reach the goal of an ion source required by the **New proton driver** in several steps. This proposal represents the first step. It is a fairly short program (one year) and requires moderate investment (a new hire plus \$60k M&S funds). This effort may have an immediate impact on the present Linac and Booster performance. This is because these new sources can be mounted on the Cockcroft-Walton and provide an H<sup>-</sup> beam with higher intensity and better quality (*i.e.*, a brighter beam).

Decreased beam size in the Linac should decrease the beam loss and radiation allowing a higher intensity and repetition.

## 2. R&D goals:

### (a) Improvement of the magnetron:

The emittance (brightness) of the present magnetron can be improved by optimizing the discharge geometry, gas injection, extraction and plasma over-neutralization. The goal is to attain 85 mA of  $H^-$  with an emittance of  $0.5 \text{ ? mm-mrad}$  (90% normalized, which is a factor of 2 smaller than the present beam emittance).

### (b) Development of a noiseless semi-planotron:

The goal is to obtain up to 110 mA of  $H^-$  with an emittance of  $0.7 \text{ ? mm-mrad}$  (90% normalized). This new source can be adapted for installation on the Cockcroft-Walton as a replacement of the magnetron.

As a future improvement of the  $H^-$  beam quality for the existing Linac and Proton Driver (after finishing a short R&D program) we propose to develop an  $H^-$  source giving a very high brightness, a Penning geometry Surface-Plasma Source, known as a Dudnikov type  $H^-$  source (DTS). Features of this source are: a noiseless discharge and beam formation, very high beam brightness, and the possibility to adapt to the existing injector or an RFQ.

## 1. R&D goals:

(a) Production of  $H^-$  beam with an intensity of 120 mA and brightness of 30-50% higher than the Semi-Planotron source.

(a) Adapt DTS to existing injector.

(b) Develop a source housing and a beam formation, transport, and focusing system for the RFQ.

We have a possibility in this design to incorporate an optimized combination of features for the DTS developed at BINP, ISIS, LANL, UMD, and INR. Developments at LBL and FU could be used in the LEBT.

Suppression of fast ion instability is important for production and transportation of H<sup>-</sup> beams with high brightness

1. Space charge neutralization (compensation) by residual gas ionization is efficient for DC ion beams if an electron trap is created along the beam.
2. Pulsed ion beams and beams with intensity modulation need a higher gas density for neutralization so beam loss by charge exchange or stripping of negative ion could be significant. Space charge neutralization by ions could result in fast ion instability. Over-neutralization is necessary for damping this instability.
3. Space charge neutralization needs to have a plasma with a density close to the beam density  $n_p = n_b = 10^8 - 10^9 \text{ cm}^{-3}$ . But the gas density for production of this plasma by beam interaction with the gas should be much higher  $n_g = 2 \cdot 10^{-4} \text{ cm}^{-3}$ . The corresponding level of gas ionization is very low and H<sup>-</sup> stripping could be low enough only for short transportation.
4. A plasma with a density  $n_p = n_b = 10^8 - 10^9 \text{ cm}^{-3}$  could be produced with a very low gas density by plasma generation with a pulsed plasma gun where 50% of the injected gas could be ionized.
5. The technology used for positive ion beam neutralization could be used for negative beam neutralization (compensation) and over-compensation.

## Test Stand Status

Test Stand is close to operating condition.

Now used for testing of the DC negative ion source for electron cooling and for development of plasma jet source for advanced space charge neutralization (hollow cathode discharge, vacuum arc discharge) of ion beam in LEBT after extractor and in beam line with ? magnets. Magnetron SPS installed in Test Stand.

For start the work with negative ion source for Linac it is need , as first step (after team formation):

1. inspection of power supply system (Engineer and technicians – 2weeks)

As second step:

2. Reinstallation an emittance scanner, some beam diagnostics and computer dates accusation system (Engineer and technicians 2 weeks).

First goal is a characterization of existing magnetron source: emittance scanning for optimal operation condition (Team- 2 months).

Next steps- optimization of discharge electrodes, gas pulsing system, extraction system of magnetron (team-2 months). Optimization of space charge neutralization with a plasma source (2 months).

Test long time operation (6 months).

Development of noiseless semiplanatron surface plasma source (team 3 months).

Test long time operation (6 months).

Adaptation and Testing an ISIS version of the Penning DT SPS.

## 13.3 DESCRIPTION OF THE ION SOURCE

### 1. General remarks

High-brightness, intense beams of  $H^-$  and  $D^-$  can be generated in Surface-Plasma Sources (SPS) by the interaction of the plasma flux with a surface to transfer an electron from an electrode to reflected or desorbed atoms thus forming negative ions. The efficiency of negative ion formation depends very much on the catalytic property of the surface, mainly the work-function. For enhanced negative ion formation in the SPS a mixture of substances with a low ionization energy, such as alkaline or alkaline earth elements or compounds, are used. Most efficient is the addition of cesium. Still the surface work-function and catalytic properties of the surface for negative ion formation depends very much on many parameters such as surface-cesium concentration, admixtures of other compounds, such as oxides, halides, nitrides, and surface temperature,...etc. Small changes in the surface condition dramatically change the efficiency of negative ion formation. It is a fine art and some magic to optimize the surface and plasma condition for high efficiency of negative ion formation. This condition is a strong reason for the variation in efficiency of negative ion production although conditions look very similar. Small changes in the surface condition can increase or decrease the intensity of a negative ion beam by large factors.

As an example, Fig. 1 show data from experiments with the first version of a semi-planotron SPS at BINP (1977) demonstrating the intensity of  $H^-$  and  $D^-$  beams from a 1x10 mm emission slit as a function of discharge current  $I_p$ . Beam intensity could vary from 200 mA to 10 mA for the same discharge current. Fig. 2 demonstrates a variation in the time of the intensity of a negative ion beam at the ISIS facility. This data demonstrates a very strong variation of beam intensity and the importance and difficulties of optimization for stable production of the highest beam quality.

It is easier to have stable operation with relatively low beam parameters such as  $I \sim 30-50$  mA,  $J \sim 0.5-1$  A/cm<sup>2</sup>,  $T_i \sim 5-10$  eV. Present experience permits better optimization for long stable production of high-brightness high-intensity beams of negative ions ( $I \sim 0.1-0.15$  A,  $B \sim J/T_i > 1$  A/cm<sup>2</sup> eV,  $N > 10^8-10^9$  pulses). Fig. 3 show noiseless operation of an SPS (shown in Fig.4) with high intensity and brightness. Highest brightness could be reached only with noiseless operation. Fig. 5 demonstrates production of a noiseless discharge by the small addition of  $N_2$ . A transition from noiseless discharge to noisy mode of operation decreased the brightness by 10 times or more.

## 2. Negative Ion Source for Charge-Exchange Injection

The first versions of the Surface-Plasma Sources (SPS) developed for charge-exchange injection of protons have an operating intensity  $I \sim 50$  mA with pulse lengths of 0.05-1 msec and a repetition rate up to 50 Hz.  $H^-$  beam parameters of these SPS was sufficient for normal operation of large proton accelerator complexes during the past 25 years without significant modernization of ion sources. Now, new accelerator projects need an increase of the ion beam intensity and brightness. Some upgrading of existing SPS could achieve the necessary increase of intensity, duty factor and beam quality without degradation of reliability and availability of the achieved satisfaction level.

The Fermilab Magnetron SPS has been operational since 1978. The peak current of the  $H^-$  ion beam at the exit of the 750 keV accelerator column is  $I_b = 65$  mA with an extraction voltage  $V_{ex} = 20$  kV, and  $I_b \sim 70$  mA with  $V_{ex} = 25$  kV with a beam pulse length  $T = 0.075$  msec at 15 Hz. The pulse length could be increased significantly with a new arc discharge pulser and adjusted parameters. It is useful for stable operation to have a discharge power supply as a current source with a high impedance ( $Z = 5-10$  Ohm, now  $Z = 1$  Ohm) and corresponding higher voltage. Optimization of the discharge electrode configuration should help to increase the intensity up to  $I_b = 0.1$  A without increasing the discharge power above acceptable levels. Gas delivery optimization should allow a longer pulse and higher intensity without an increase of the gas loading.

An optimized extraction system with a suppression electrode should improve the beam intensity, beam quality and beam space-charge neutralization with a low gas pressure. A suppression of the positive ion extraction to the accelerating gap should suppress cathode and anode sputtering by accelerated positive ions - a main reason for the short ion source life-time. Improved cathode and anode cooling is necessary for increased discharge pulse length and intensity. The semi-planotron version of the SPS is good for operation at higher duty factor.

From previous experience it is possible to have reliable operation of a SPS with parameters: Peak current after extraction (bending magnet)  $I_b \sim 0.12-0.15$  A with pulse duration of  $T \sim 1$  msec, repetition rate  $F = 15$  Hz.

A possible SPS with these parameters was tested with a relatively long run. Still a SPS adapted for long operation in the Linac environment will need work. For ion source optimization and testing it is necessary to resume operation of the test stand and to upgrade some of the equipment. For prototyping of the equipment it is possible to use previous developments from FNAL, ANL, BINP, UMD, BNL, ISIS, and DESY.

Of interest is the RF ion source from DESY. It is possible to test this version of ion source by using a RF proton source from NEC as a prototype. Relative simple modifications could be made for testing this possibility.

### 3. Lifetime of Negative Ion Sources

- 1 The lifetime of ion sources with a cold electrode discharge is limited by cathode (electrodes) sputtering and the formation of flakes. The flakes can create a short circuit of the discharge electrodes, close the emission aperture, or initiate a discharge instability and arcing. Deposition also changes the surface properties and efficiency of ion formation. Sputtering rates increase with energy of the bombarding ions (increase of discharge voltage), and with increase of the ion mass and charge. Different materials could have a very different sputtering rate.
- 2 A small admixture of cesium or other substances with a low ionization potential could be used to decrease the discharge voltage and significantly reduce the sputtering rate. These admixtures are used as catalyses of negative ion formation in the surface-plasma interaction in the Surface-Plasma Sources (SPS). In this application cesium is used as a thin (fraction of a monolayer) film on the surface to lower the work function  $\phi$  from 4 eV to 1.6 eV. This increases the probability of secondary negative ion emission up to hundreds of times. This also decreases the number of sputtered atoms on the electrodes per an emitted negative ion by many orders of magnitude.

- 3 Presently the SPS lifetime is limited through the sputtering of the cathode or anode due to back accelerated high energy positive ions and flake formation from this deposit. The intensity of back accelerated positive ions could be suppressed using a 3 electrode extraction system with a suppression electrode which reflects positive ions from the ion beam and improves the space charge neutralization. This improves the beam quality and stability of the ion source operation.
- 4 4 Optimized cesium film recycling (deposition-desorption) could be used for shielding of electrodes from the sputtering and can reduce the sputtering to a very low level. Cesium in a SPS acts as an oil in an engine increasing the operational lifetime. “Cold Start” of a discharge without cesium for a few minutes could be more destructive than many hours of low voltage operation. Emission current density of  $H^-$  up to  $J \sim 1 \text{ A/cm}^2$  have been observed in discharges without cesium. A fingerprint with a trace of Na or K could increase the efficiency of  $H^-$  production significantly. The power density in a discharge without cesium is very high and the sputtering rate is much higher. Electron emission from ion source without cesium is very high.

### 3. Low Energy Beam Transport

1. An ion beam from a compact SPS has a very high current density ( $j \sim 1-3 \text{ A/cm}^2$ ) and perveance. For transport of these beams it is necessary to use a deep space-charge neutralization (compensation) or very strong continuous focusing by electrostatic forces as in the RFQ.
2. Partial compensation of space charge with magnetic focusing and nosy operation will create a strong variation of focusing and lead to an increase of emittance by ellipse oscillation. Still, this mode of transport is used in almost all injectors, and until recently it was acceptable. Space charge compensation by ions have some difference from the compensation by electrons. Ion oscillation in the potential of the beam is more coherent and can be a reason for very strong and fast beam-ion instability. Beam-ion instabilities have been observed recently in the electron beam of the Advanced Light Source (LBL) with increased residual gas density. In low energy negative ion beams this instability has been observed many years ago (1976). A development of this instability along a 15 keV  $\text{H}^-$  beam, at 70 mA is shown in Fig. 6. Coherent oscillations of positive ions in the beam potential excite quadruple and dipole oscillation of the  $\text{H}^-$  beam, and developed a decompensation and emittance growth.

3. To eliminate this problem many versions of an electrostatic focusing-transport LEBT have been proposed. Now under development is an ELEBT for SNS. The electrostatic LEBT developed at LBL is shown in Fig. 7. Transport of a  $H^-$  beam of energy 65 keV with intensity up to 42 mA has been demonstrated. Significant R&D for the development of an electrostatic LEBT operating at higher intensity is necessary.
4. The beam-ion instability could be damped by over-neutralization of the beam, changing the sign of the beam potential with an increase of the ion density in the beam. This process is shown in Fig. 8. A typical dependence of the beam potential versus gas pressure is shown in Fig. 9. With increased ion and electron density a stable beam transport could be reached with additional focusing by reversed space charge. This solution could be used for a short transport with acceptable levels of ion loss by stripping. This solution is convenient because it is possible to locate a second (spare) ion source in front of one RFQ. Ion beam pulses from this ion source could be long enough for reaching a deep over-neutralization.
5. A good solution could be a short LEBT with a fast beam over-neutralization by streams of noiseless plasma from a separate plasma source. With magnetic focusing, beams from 2 SPS could be steered to the entry of the RFQ. Close-coupled systems have been tested in ion implantation. Good neutralization decreases the beam emittance  $\sim 2$  times.

## References

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  2. J.Peters, LINAC' 99.
  3. J.Peters, Negative Ion Sources for High Energy Accelerators, Rev. Sci. Instrum., 71(2),1069 (2000).
  4. J.Peters, EPAC'2000.
- H. Zhang, Ion Sources, Springer,1999

## Negative Ion Source for Charge- Exchange Injector

Introduction a Cesium Catalysis for negative ion production in the Surface Plasma Sources (SPS) was so efficient that have allow to become a high efficiency Charge-Exchange Injection of proton into high energy accelerators and storage rings. First versions of the Surface- Plasma Sources (SPS) developed for Charge - exchange injection of protons have an operating intensity  $I \sim 50$  mA in pulses 0.05- 1 msec with a repetition rate up to 50 Hz. H- beam parameters of these SPS was enough for normal operation of big proton accelerator complex during near 25 years without significant modernization of ion sources. Now a new accelerator projects need an increase of ion beam intensity and brightness.

Some upgrading of existing SPS could be used for a necessary increase of intensity, duty factor, beam quality without a degradation of reliability and availability from the reached satisfaction level.

Fermilab Magnetron SPS is under operation since 1978.

Peak current:

The peak Current of H- ion beam at the exit of the 750 keV accelerator column is  $I_b = 65$  mA with an extraction voltage  $U_{ex} = 20$  kV, and  $I_b = 70$  mA with  $U_{ex} = 25$  kV and the beam pulse length  $T = 0.075$  msec.

A pulse length could be increased up to  $T = 1$  msec by use a new arc discharge pulser with necessary parameter. It is useful for stable operation to have power supply as a current source with a higher impedance as  $Z = 5-10$  Ohm ( now  $Z = 1$  Ohm) and correspondent higher voltage.

Optimization of the discharge electrodes configuration should help to increase an intensity of up to  $I = 0.12-0.15$  A without increase of the discharge power above acceptable level.

Gas delivery optimization should perme ate to have a longer pulse and higher intensity without increase of the gas loading.

An optimized extraction system with a suppression electrode should improve a beam intensity, beam quality and beam space charge neutralization- transportation with a low gas pressure. A suppression of the positive ion extraction to the accelerating gap should suppress a cathode and anode sputtering by accelerated positive ion - a main reason of the ion source component degradation.

Improve of the cathode and anode cooling is necessary for increase a discharge pulse length and intensity.

Semi-planotron version of SPS is good for operation with a higher duty factor. Cathode cooling could be improved significantly in semi - planatron version of SPS.

H- beam with high brightness have been produced from the semi - planotron.

From previous experience It is possible to have a reliable operation of SPS with a parameters:

Peak current after extraction ( bending magnet)  $I_b = 0.12-0.15$  A with pulse duration of  $T = 1$  msec, repetition rate  $F = 15$  Hz.

A possibility of a SPS operation with these parameters was tested in the long time run. For Ion Source optimization and testing is need to star the operation of test stand and development and upgrading of some equipment. As a prototypes of equipment it is possible to use previous development of the FNAL, BINP, UMD, BNL, ISIS.

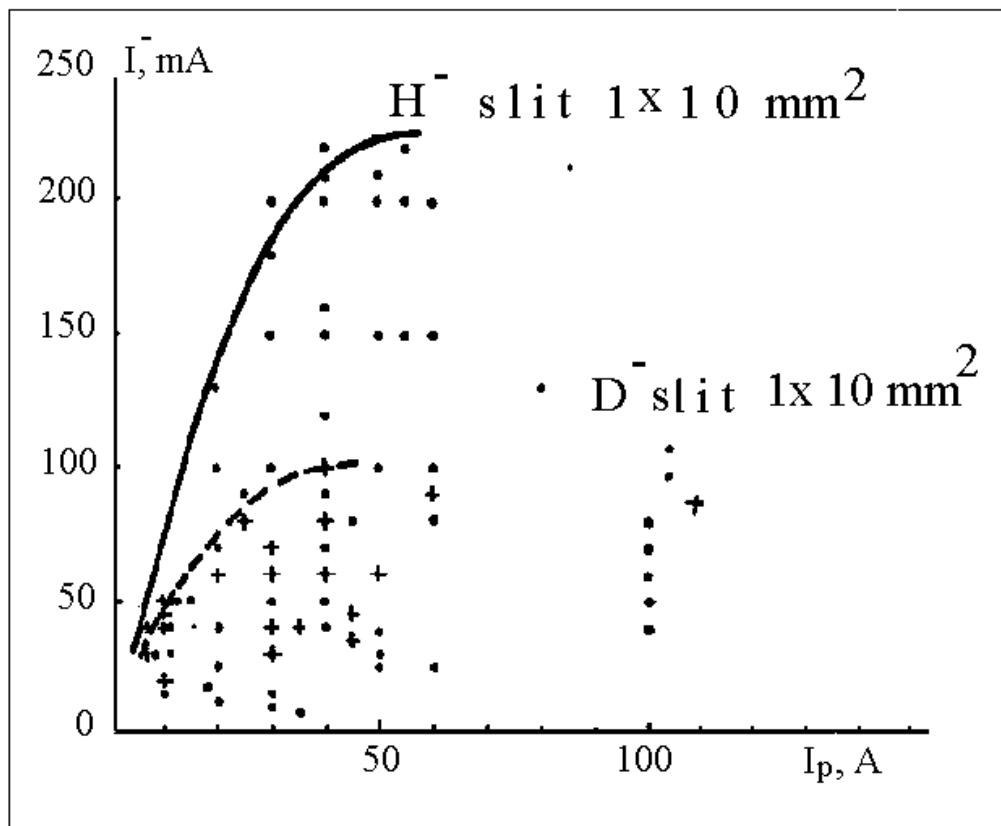


Fig.1

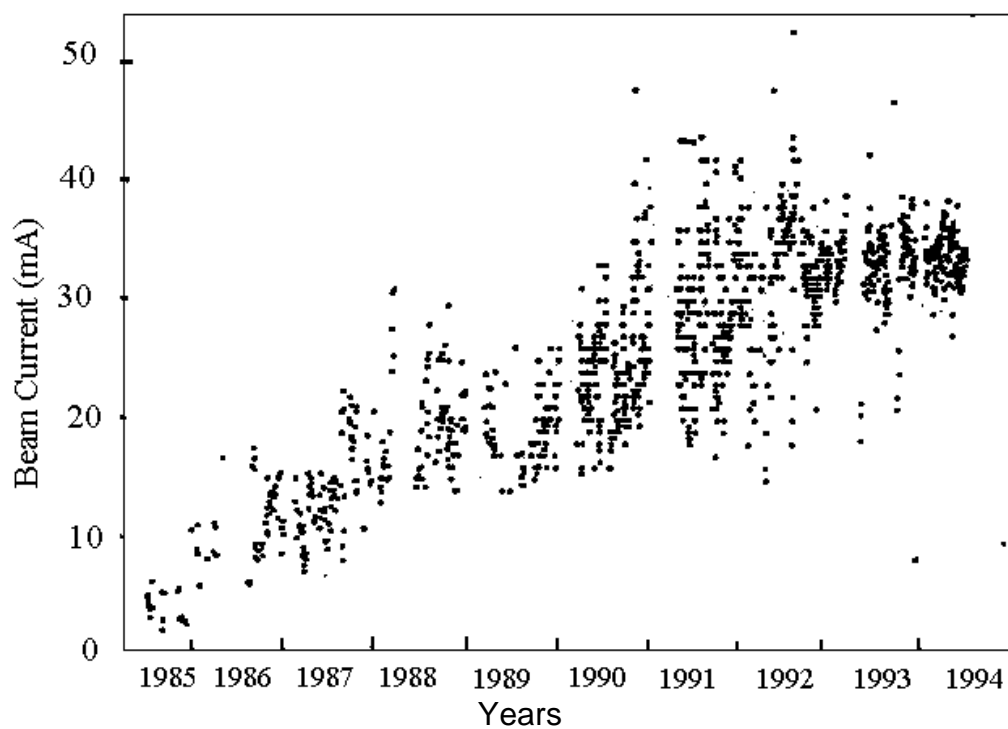


Fig.2

repetition  $f_0 = 100 \text{ Hz}$   
 Penning (Dudnikov type)  $\text{H}^-$  SPS

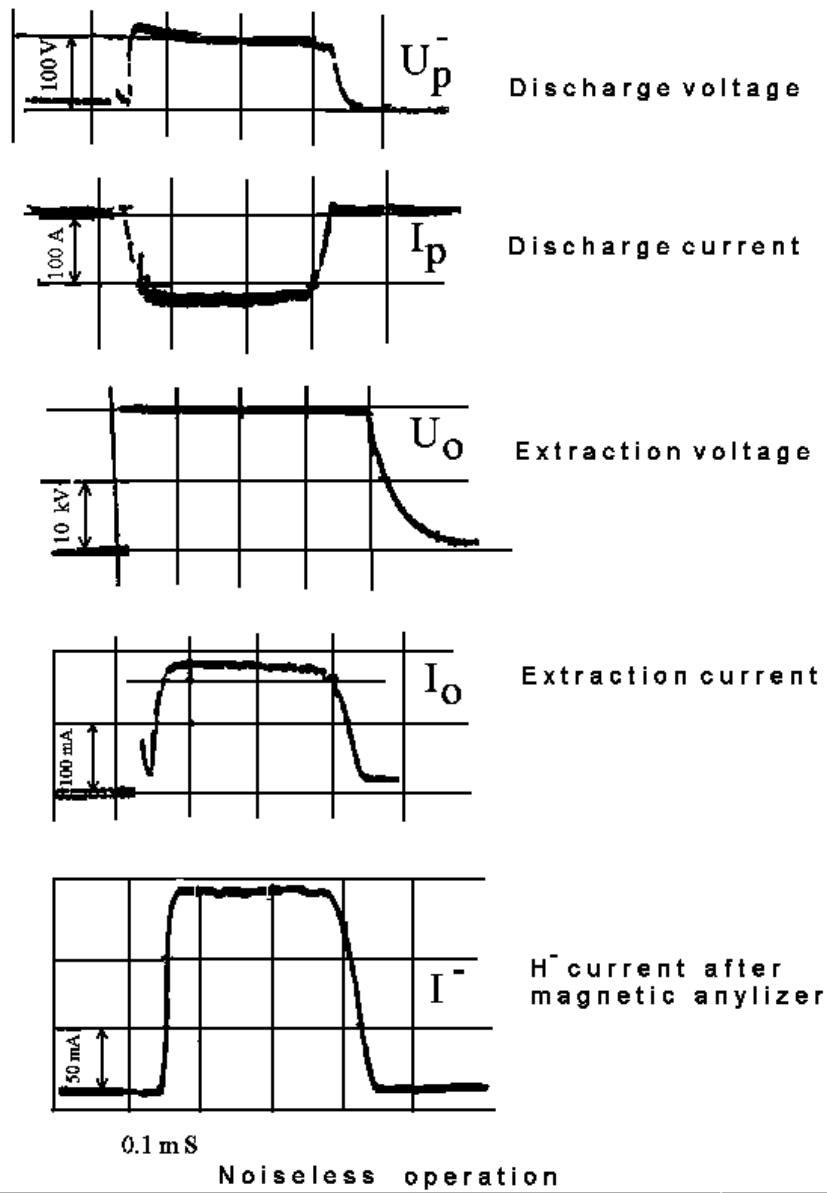


Fig.3

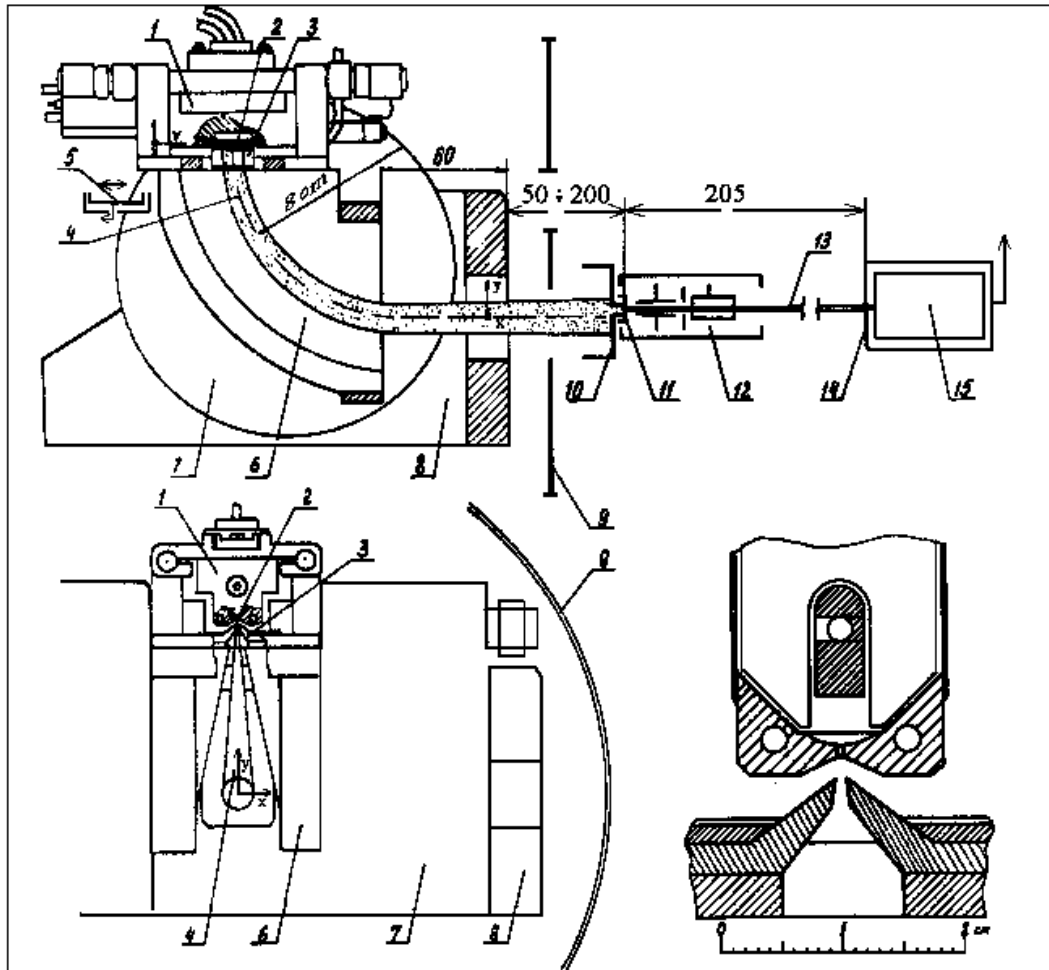


Fig. 4. Surface- plasma ion source, beam formation and diagnostics.  
 1- gas-discharge chamber; 2- emission slit; 3- extraction electrode; 4- negative ion beam;  
 5- moving collector one; 6- magnetic poles; 7- magnetic coils; 8- magnetic yoke; 9-  
 ion source shielding; 10- moving collector two; 11- collector for current density  
 measurement; 12- deflection system; 13- ion beam let; 14- shield with analyzer aperture;  
 15- collector.

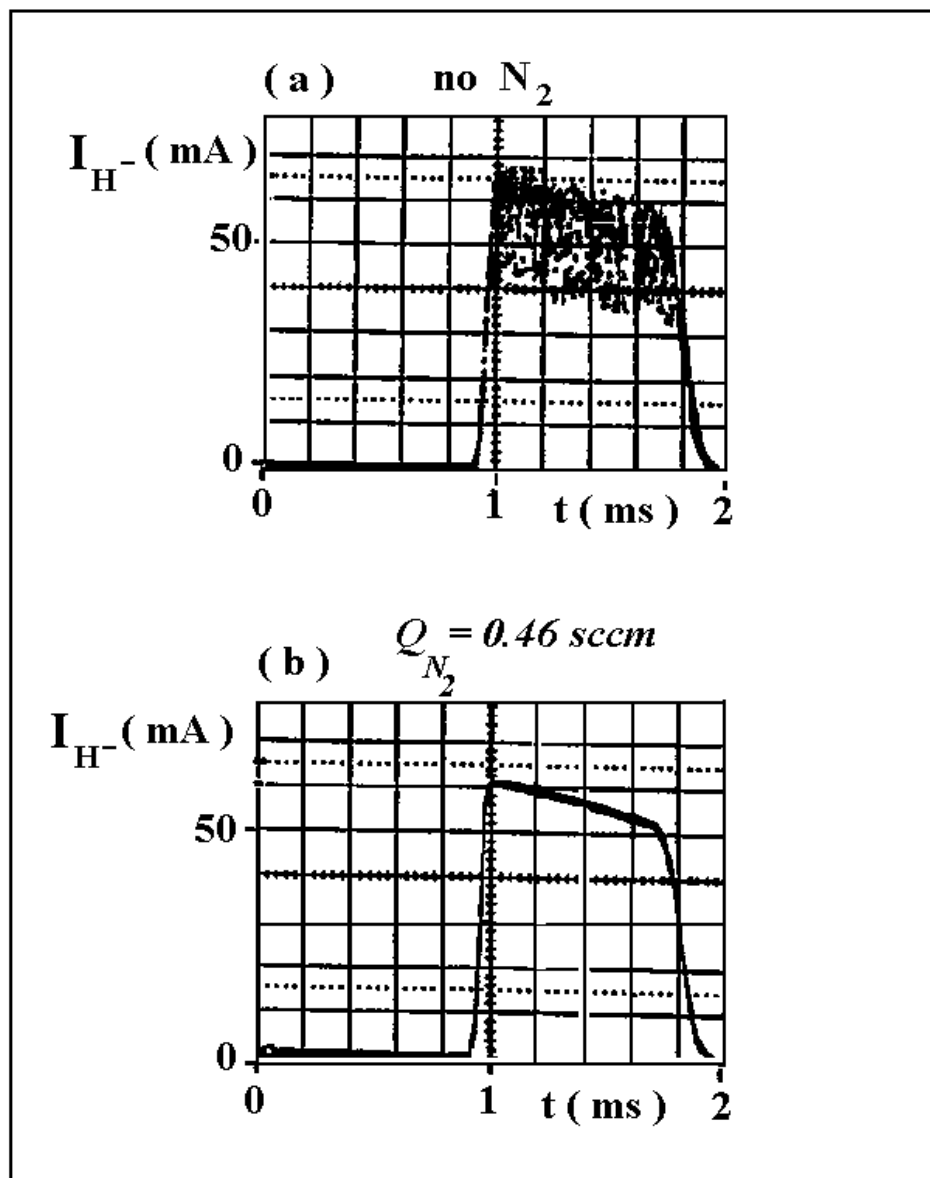


Fig.5

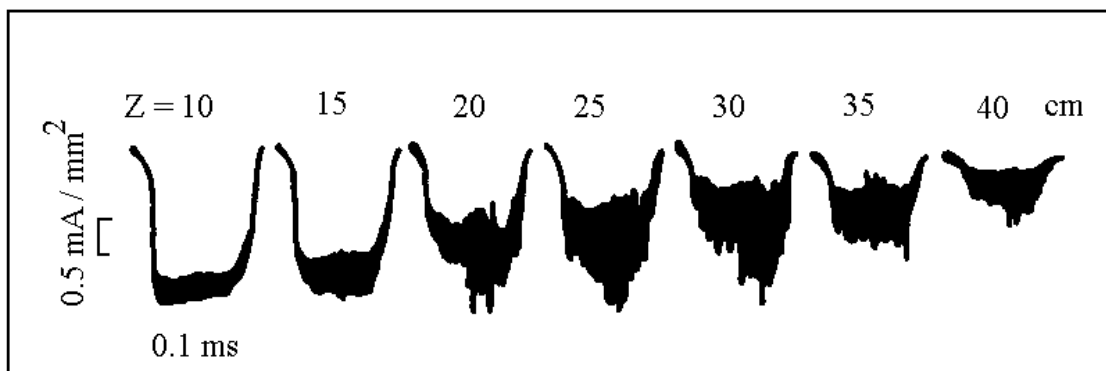
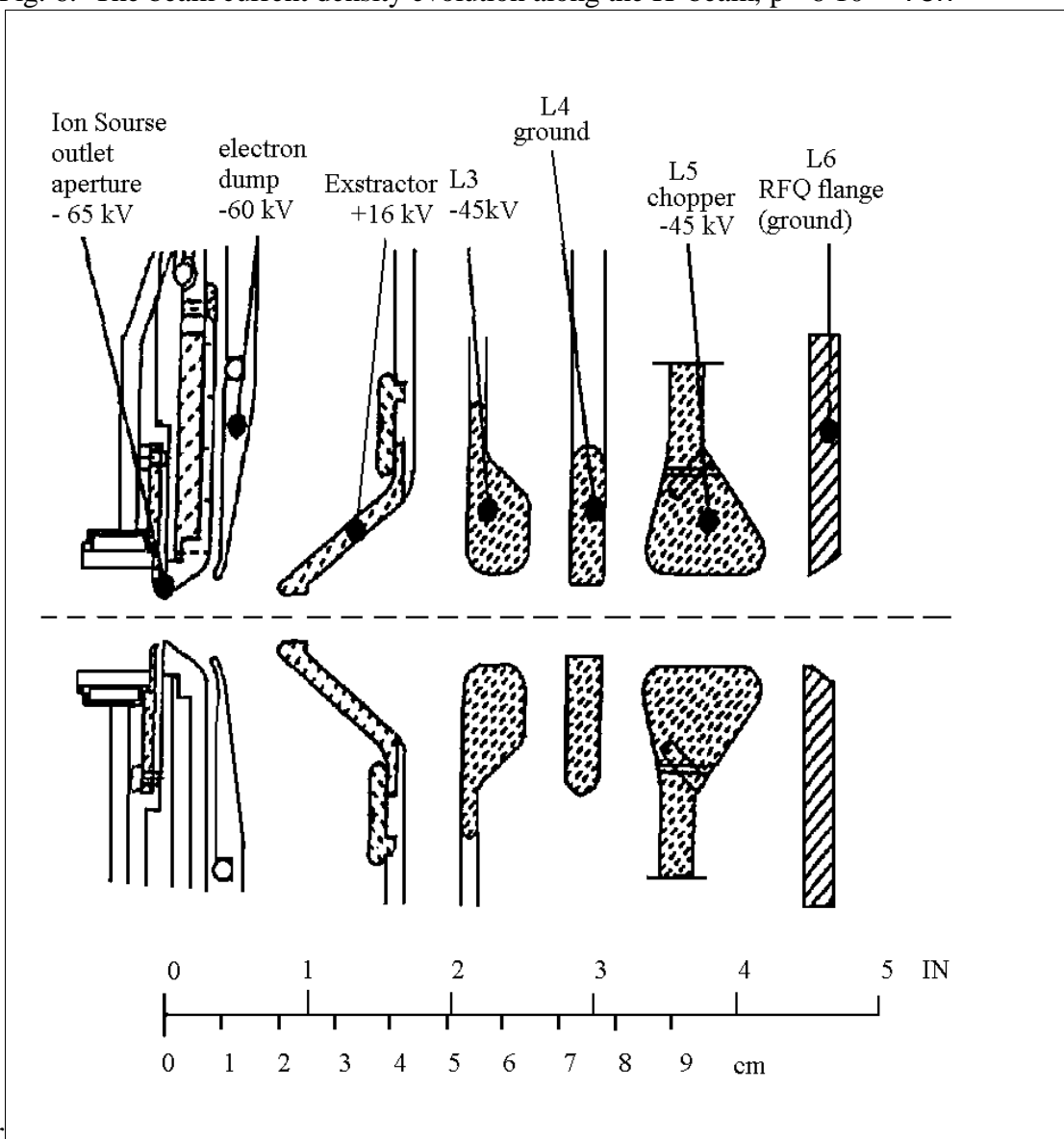


Fig. 6. The beam current density evolution along the  $H^-$  beam,  $p = 6 \cdot 10^{-4}$  Torr



ig. 7 Cross section of LEBT electrodes with ion source outlet aperture, electron dump, and REQ endwall (LBL, for NSNS).

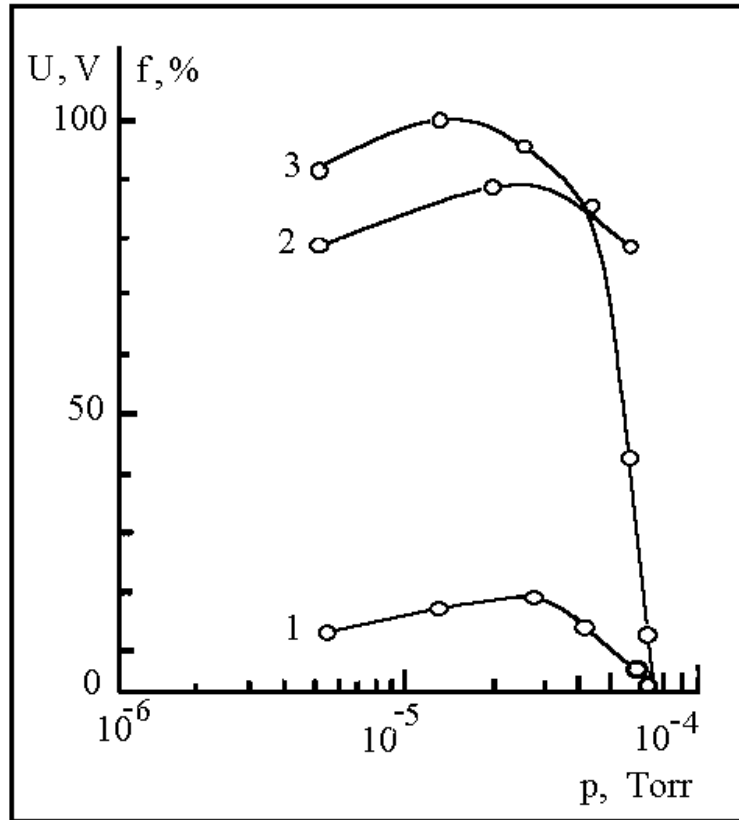


Fig.8. Dependences of the amplitude of potential oscillation  $U$  (3), The pulsation coefficient  $f$  of the total current (1) and current density (2) on the gas pressure at  $Z=45$  cm from the bending magnet.

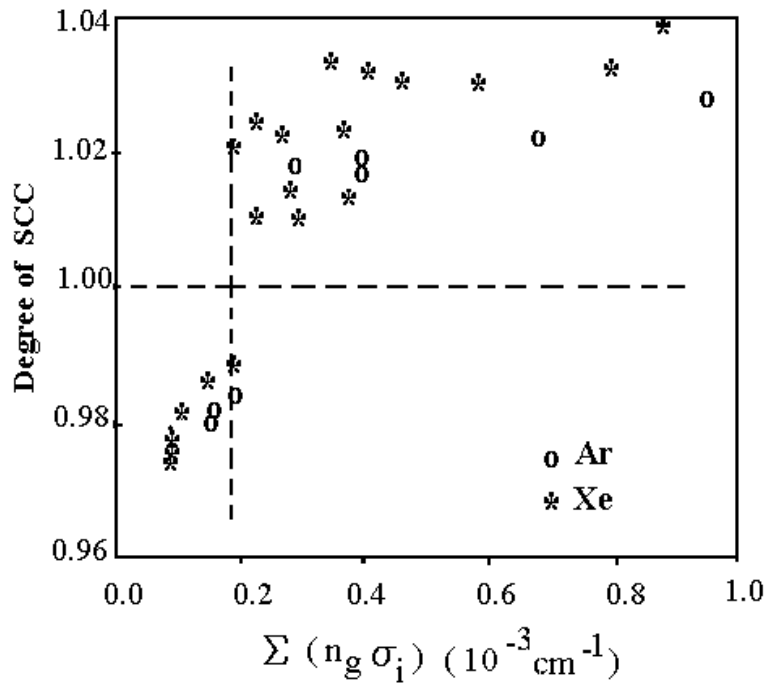


Fig. 9. The degree of  $H^-$  beam space- charge compensation vs.  $\beta (n_g \beta_i)$ . The charge from  $f < 1$  to  $f > 1$  occurs at the threshold  $\beta (n_g \beta_i)$ .